Commissioning of the LHC Injectors BWS Upgrade

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IBIC 2021
TUPP18

Abstract: A novel generation of fast Beam Wire Scanners (BWS), developed in the framework of the LHC Injectors Upgrade (LIU), has been recently deployed in the 3 LHC injector synchrotrons, accelerating protons from 160 MeV to 450 GeV, during the 2019-2020 LHC long shutdown. The monitors feature high precision motor controller, high resolution wire position monitoring and wide dynamic range secondary particles detectors. This contribution will document the commissioning of the 17 new systems during the accelerator complex restart in 2021, which is an exiting and challenging phase in the life cycle of an instrument. A summary of these so far achieved levels of reliability, reproducibility, detectors/DAQ bandwidth and overall accuracy, will be used to revisit the options for further improving the systems' performance in the future.

LIU BWS INSTRUMENT

Fast Beam Wire Scanner (BWS) systems are commonly used in synchrotrons to monitor transverse beam sizes. They are based on kinematic units designed to move very thin wires at high speed through a particle beam. The wire-beam interaction generates a shower of secondary particles that is typically measured by a scintillator coupled to a photo-multiplier tube. The correlation between the wire position and the intensity of the secondary particles shower allows the determination of the transverse beam size.

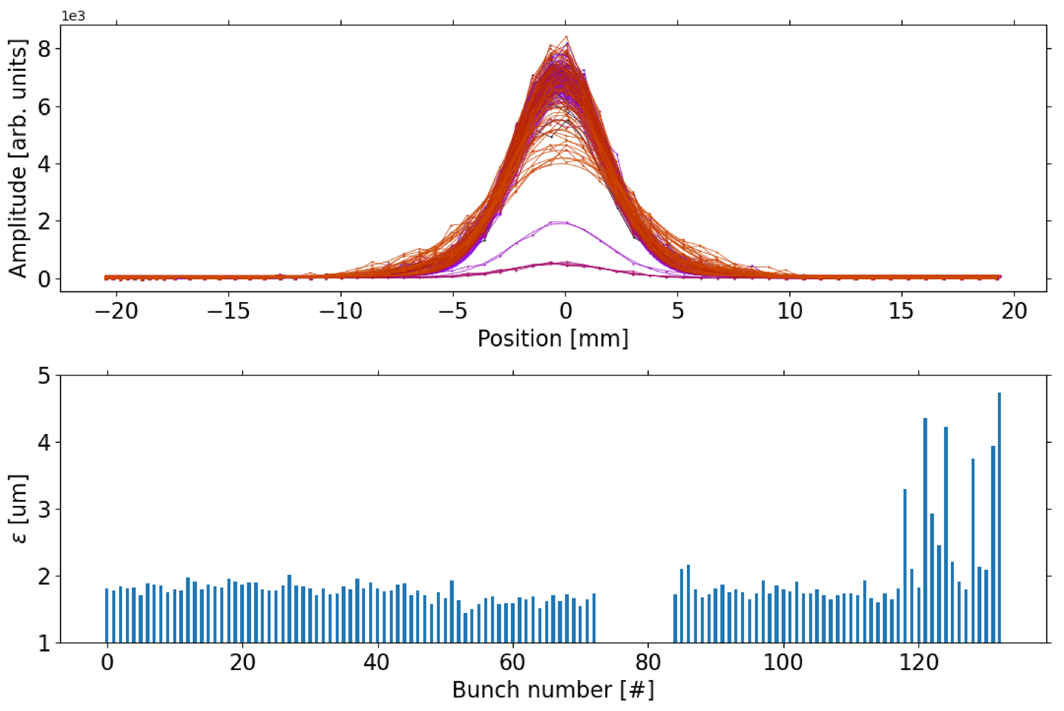

Figure 4: LIU wire scanner BWS.41677.V measurement in the SPS (top) of 25ns separated bunches (LHC Type beam). The beam emittance growth at the end of the train is due to the electron cloud effect (bottom).

ARCHITECTURE

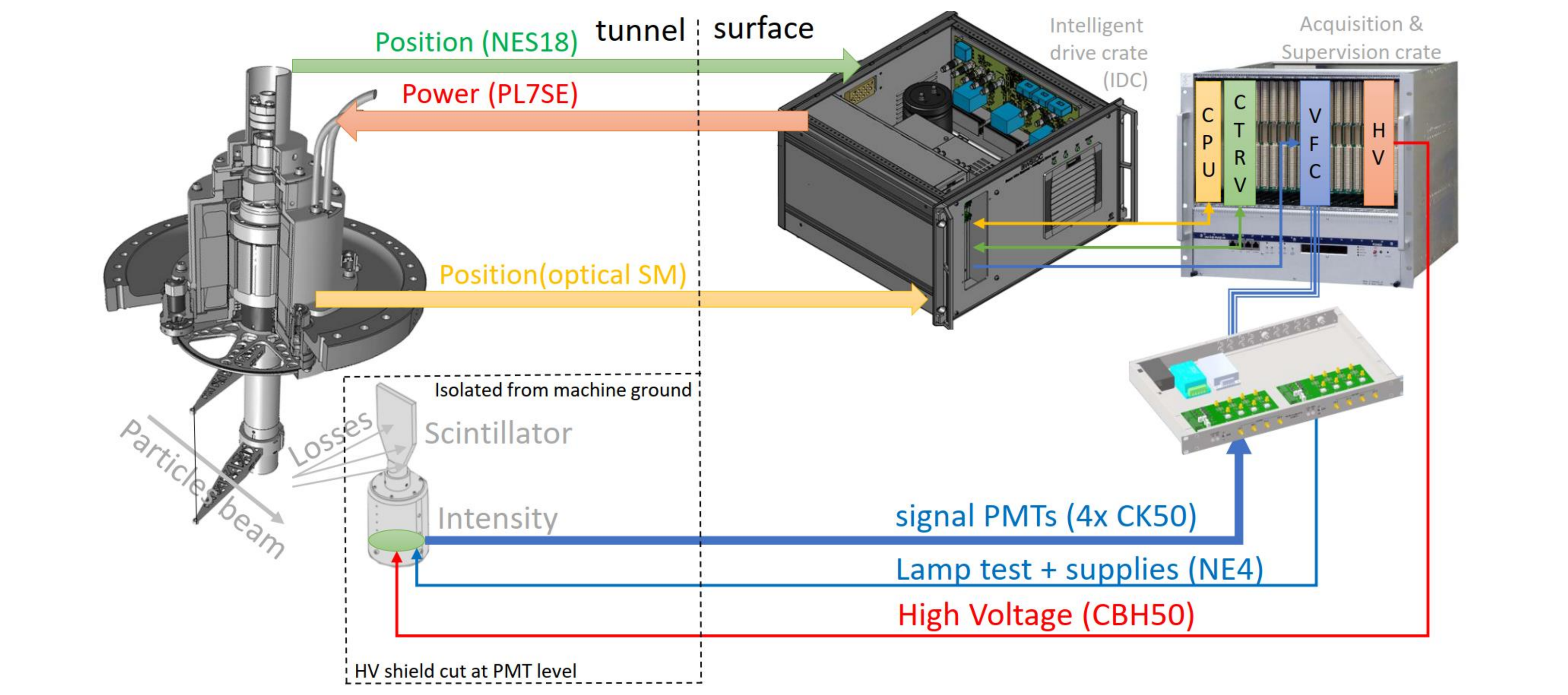

Figure 1: The kinematic unit and particle detectors (left side) are located in the accelerator tunnel. The stand-alone control unit and the VME acquisition system (right side) are in the surface service area. The communication from the tunnel to the surface is done with cables and optical fibers, with lengths above 150 m in some cases.

INDIVIDUAL SYSTEM TESTS

The Individual System Tests (IST) at CERN are the overall verification by experts of a system before the HW and Beam commissioning carried out by the accelerator operation crew. For the wire-scanner, multiple procedures are run:

- Open Loop Test (OLT) verifies the cabling, electronics and sub parts of the kinematic unit shown in Fig. 2.
- Scan Without Motion (SWM) performs a scan procedure without the carbon wire going through the beam.
- PMT Lamp Test (PLT) uses a lamp in front of PMTs to verify the acquisition chain.
- Optical Encoder Test (OET) finds setting for the sensor giving the carbon wire position.
- Series of 100 scans to analyse the angular Trajectory Reproducibility Error (TRE) shown in Fig. 3.

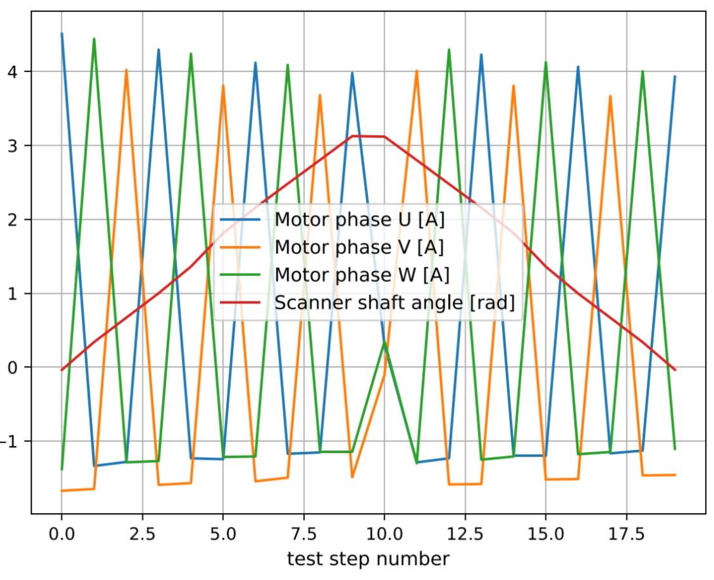

Figure 2: Motor currents and shaft angle of scanner PS.64.V during an Open Loop Test (OLT) checking the scanner connectivity and kinematic unit rotation.

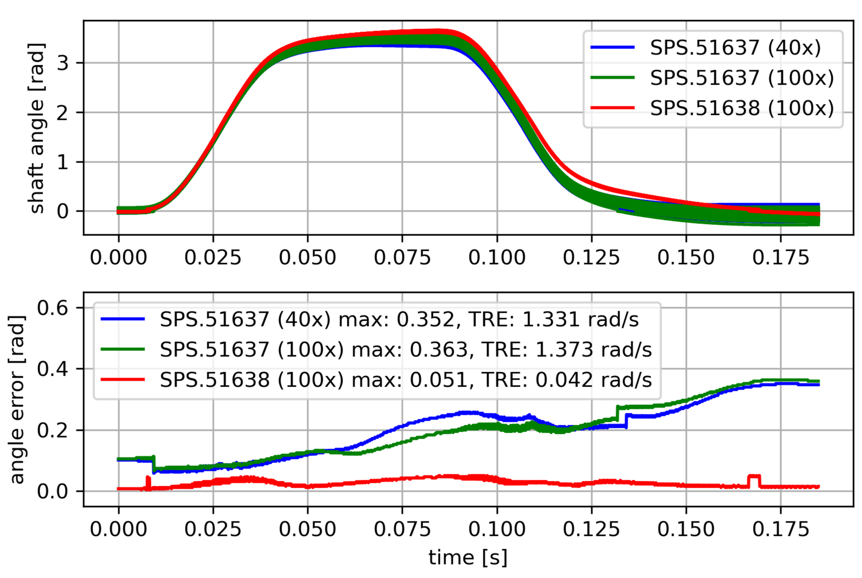

Figure 3: Kinematic unit angular trajectory for sets of scans (top) and the scan to scan variation within the set (bottom). The Trajectory Reproducibility Error (TRE) expresses at which rate reproducibility degrades during the scan.

NOISE CHARACTERISATION

Table 1: LIU BWS name (N), accelerator (A), cabling length $[m]$ (L), trajectory reproducibility error $[mrad/s]$ (TRE), PMT noise $[bin]$ (N1) noise @$16kHz$ $[V^2/Hz]$ (N2).

N	A	L	TRE	N1	N2	scan*
R1H	PSB	60	21	171	0.02	2047
R2H	PSB	60	21	158	0.00	1361
R3H	PSB	60	697	88	0.00	4528
R4H	PSB	60	21	133	0.00	1572
R1V	PSB	55	232	144	0.01	1681
R2V	PSB	55	85	145	0.00	1261
R3V	PSB	55	63	95	0.00	6499
R4V	PSB	55	845	126	0.01	1431
54H	PS	185	63	1706	44.1	2866
64V	PS	230	63	901	8.04	2797
65H	PS	232	106	492	1.04	1028
68H	PS	215	21	522	2.15	331
85V	PS	216	85	1634	19.2	497
41677V	SPS	170	169	487	0.36	4517
41678V	SPS	170	63	155	0.12	325
51637H	SPS	150	1373	378	0.63	2040
51638H	SPS	150	42	2526	0.88	1095

*Total of 35'876 scans (up to 01.09.2021)

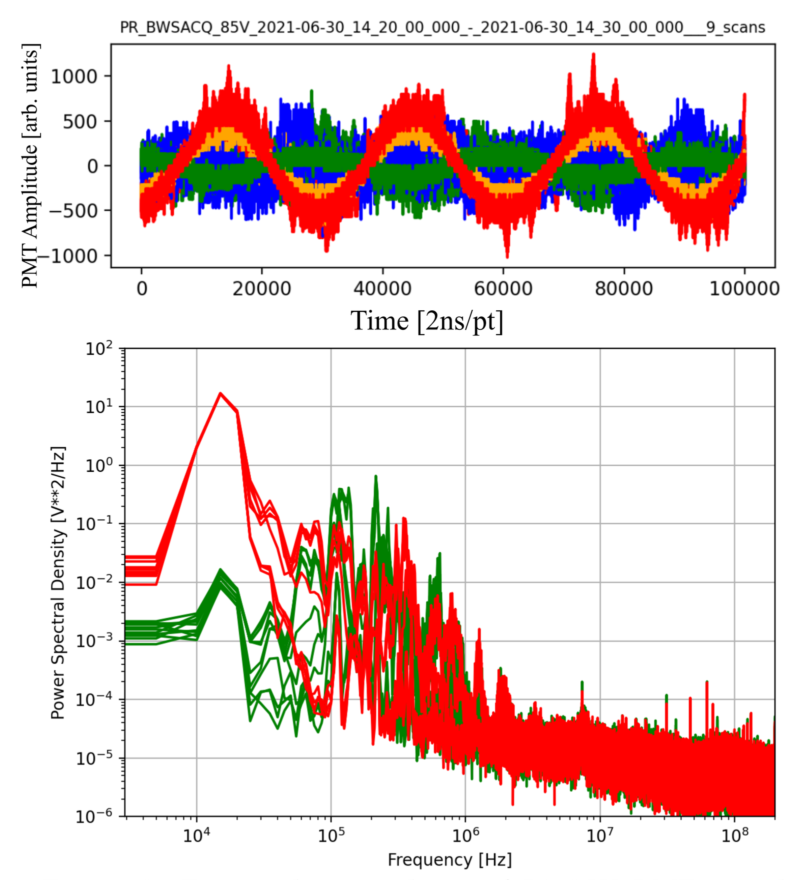

Figure 8: Temporal noise shape of PS-85V PMT signals without beam (top) and Power Spectral Density (bottom) of one of the channels (9 scans in red) and the same with a common mode noise suppressor choke (11 scans in green).

COMMISSIONING WITH BEAM

The BWS development before the 2019-2020 Long Shutdown (LS2) included the test of various prototypes with beam in the PSB, PS an SPS [3, 11, 12]. The commissioning with beam of the final systems in 2021 took several weeks in the PSB, especially to fully deploy and validate the latest FW and SW versions. On the other hand, in the PS and SPS, thanks to the experience in the PSB and benefiting of the systems' standardization, it was possible to acquire beam profiles from the first day of beam operation.
With the first milestone of handing over all systems to operation, the challenging phase of maximizing availability and optimizing the overall systems' accuracy is ongoing. For the acquisition chain, the following aspects are particularly relevant to set up and characterize in order to assess and improve performance: operating point (PMT high voltage) with Fig. 5 and 6, digital integration phasing with Fig. 7, noise reduction/rejection with Fig. 8 and bandwidth characterization with Fig. 9.

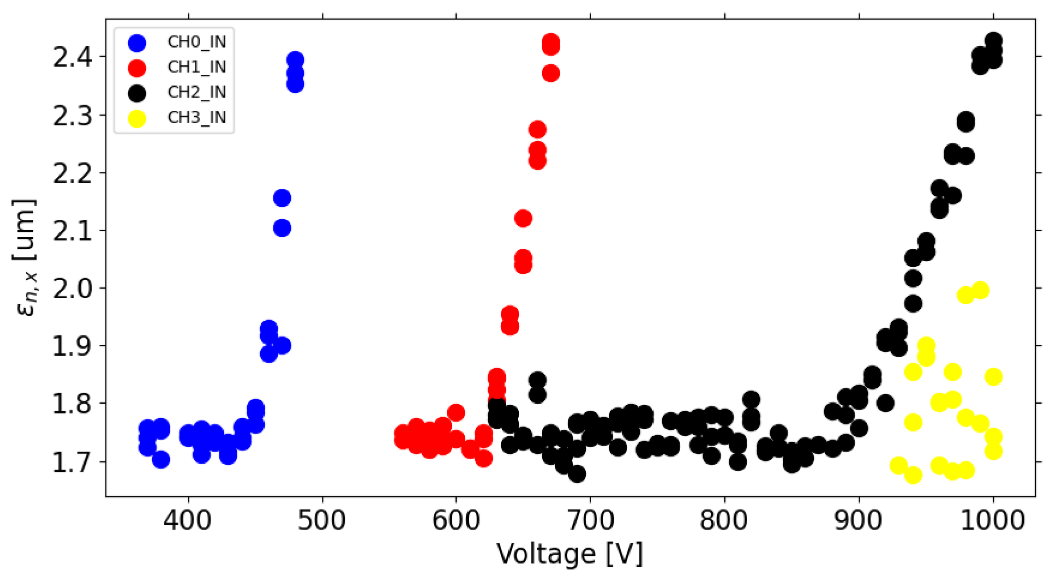

Figure 6: PSB R1V voltage scan, LHCINDIV beam, Intensity:9.4x1010ppb, Energy: 2018 MeV.

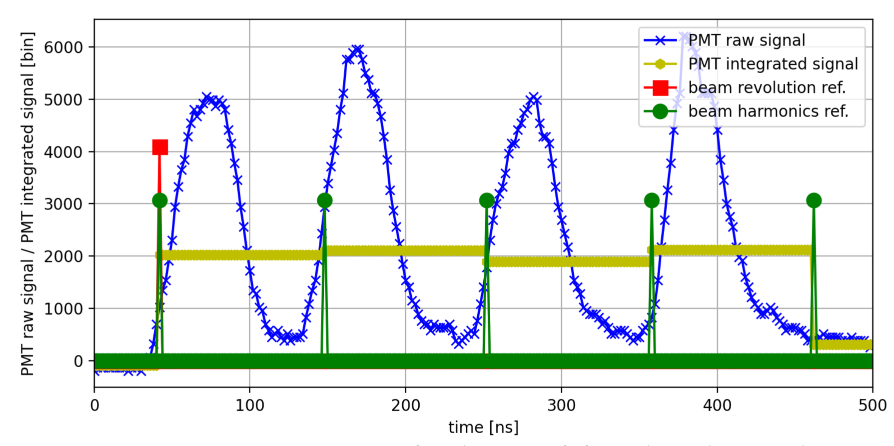

Figure 7: Raw PMT capture of a beam of four bunches withPS.65.H (blue), digitally integrated signal (yellow), beam revolution reference (red) and beam harmonics reference (green).

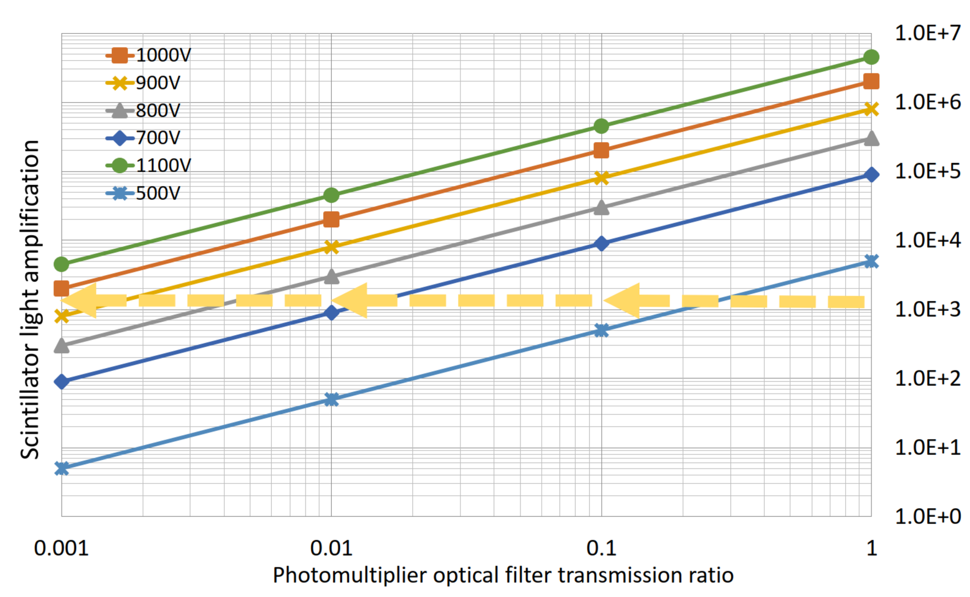

Figure 5: The scintillator light amplification (axis y) com-bines the 4 PMT optical filters (axis x) and the PMT voltage(coloured lines). The dashed line represents an approximation of the amplification set for the measurements in Fig. 6.

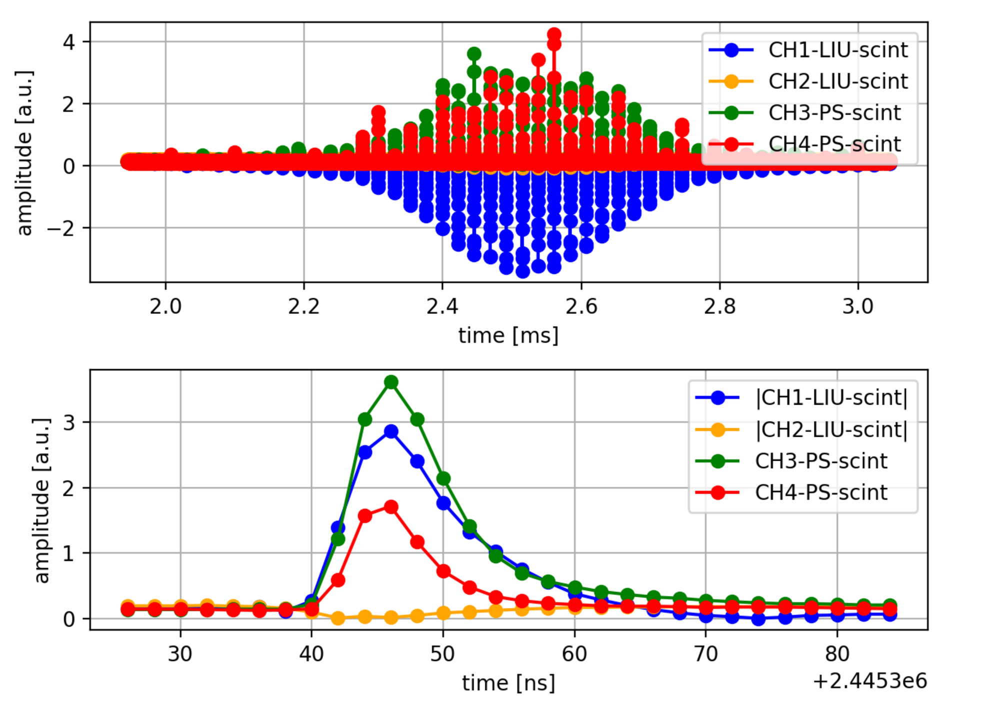

Figure 9: SPS measurements with LIU-type scintillator and preamplifier (red, green), and PS-type scintillator without preamplifier (blue, yellow). The time structure of a bunch shows similar decay for both systems (bottom) while the PS overall signal is poorer (top).

SUMMARY

The 17 new wire scanners installed in the LHC injectors were all commissioned in a relatively short time given the system complexity. They are daily, extensively used (thousands of scans already in the first few months) by the operation crews, with no major faults. This first operation period already proved the systems' capability to measure 25ns spaced bunches with few % cross-talk and with a few % statistical error (always difficult to decouple form bunch per bunch and shot by shot beam jitters). More time and dedicated measurements are needed to assess the systems' absolute accuracy and resolution.
Studies are ongoing to tune and optimize PMT operating ranges, synchronization with the beam, noise and bandwidth. Finally, new features are under development, like for detecting the PMT linearity limits, improving the measurement precision by reducing the wire speed and increasing the scan repetition rate up to bursts of several consecutive scans on the same circulating beam.

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